HEAT TRANSFER ANALYSIS OF A DATA CENTRE

KABILDEV A/L ARUMAINATHAN

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2020

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KABILDEV A/L ARUMAINATHAN

RESEARCH PROJECT SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF MECHANICAL ENGINEERING

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2020

UNIVERSITY OF MALAYA

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Name of Candidate: Kabildev A/L Arumainathan

Matric No: KQK180026 (17014438/1)

Name of Degree: Master of Mechanical Engineering

Title of Research Report: Heat Transfer Analysis of a Data Centre

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HEAT TRANSFER ANALYSIS OF A DATA CENTRE

ABSTRACT

Data centres are an integral part of networking as it houses servers that facilitate incoming and outgoing data flow. A resolute cooling approach is needed to overcome the hot air dissipated by these servers. This research focused on the computational fluid dynamics (CFD) simulation of the heat transfer modelled upon Telekom Malaysia (TM) City's data centre 3. The simulation was carried out to ascertain the heat distribution across the data centre by using ANSYS Fluent. The results indicated that the server racks' inlet temperature reaches 29.79 ^{o}C, which is close to the maximum permissible limit according to recommendations provided by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). The temperature level was elevated due to exhaust air recirculating from the hot aisles into the cold aisles. This issue was addressed by equipping a cold air containment system (CACS). The findings demonstrated a decline in maximum temperature at the front portion of the server racks to 26.98 ^{o}C and the temperature was spread more homogenously. Correspondingly, the hot air recirculation issue was surmounted by the CACS. Overall, the cooling of the servers was substantially improved with the containment system in place.

Keywords: Data Centre, Cold Aisle Containment, ANSYS, CFD, Heat Transfer

ACKNOWLEDGEMENTS

I first wish to express my sincere appreciation and gratitude to my supervisor, Associate Professor Ir. Dr. Nik Nazri bin Nik Ghazali, for giving me great advice to overcome all the obstacles that surfaced during the entire course of this research. Without his continued support, completing this research project would not have been possible.

I would like to whole-heartedly thank my mother, Madam Inthumathi Nagalingam, my family members and my coursemates for their invaluable encouragement from the start till the end. They kept me going all the way with their insightful input.

I wish to pay my special regards to all the staff and lecturers of the Faculty of Engineering at the University of Malaya for all their assistance during my study.

Lastly, I would like to thank God for giving me the strength, wisdom, and chance to embark on this research project and complete it satisfactorily.

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LIST OF SYMBOLS AND ABBREVIATIONS

TM	:	Telekom Malaysia
ASHRAE	:	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CFD	:	computational fluid dynamics
CAD	:	computer aided drawing
CRAC	:	computer room air conditioning
CACS	:	cold aisle containment system
HACS	:	hot aisle containment system
SHI	:	supply heat index
RHI	:	return heat index
RCI	:	rack cooling index
ρ	:	density
t	:	time
d	:	diameter
μ	:	viscosity
x,y,z	:	coordinates
u	:	velocity component
$\vec{V}$	:	volumetric flow rate
∇	:	divergence

P	:	pressure
G_k	:	turbulence kinetic energy generated due to mean velocity gradients
G_b	:	turbulence kinetic energy generated due to buoyancy
Y_M	:	fluctuating dilatation in compressible turbulence to the total dissipation rate
$C_2, C_{1\varepsilon}$	:	constants
σ_k	:	turbulent Prandtl number for k
σ_ε	:	turbulent Prandtl number for ε
$S_{k,}S_\varepsilon$	:	user-specified source phrase

CHAPTER 1: INTRODUCTION

1.1 Background

In this modern day and age, computers are an essential part of our lives. We rely on our digital devices to accomplish tasks on hand. With this, the need for storage space, processing power and information rises rapidly. Entities such as social networking sites, government bodies and online shopping platforms require a reliable place for data transmission to occur. This place is known as a data centre. It is a huge amenity that saves and circulates data among other things by accommodating computers and networking paraphernalia. (Athavale et al., 2018). They stated that a data centre can be broken down to three main parts. First, the data processing appliance, which is the heart of the data centre. Second, cooling scheme to lower the heat of the data processing appliance. Third, power distribution unit (PDU) that powers the data processing and cooling devices.

Figure 1.1: Typical data centre layout (Henessy, 2016)

There are many servers, usually in the thousands depending on the operation being facilitated, running at any given time in a data centre. All these servers are strategically placed on racks that are arranged in rows. For all these servers to be running continuously without being interrupted, a proper cooling arrangement and constant power is required. Heat is a crucial factor when it comes to the optimal performance of these servers.

A proper feasibility study needs to be done before the data centre is constructed as the number of servers to be used will determine the amount of necessary cooling required. By identifying the right amount of cooling needed, electricity can be saved on the long run which in return will substantially lower the overall operating costs. Many companies utilize data centres to supplement their operations. One of them is our very own telecommunications giant, Telekom Malaysia (TM). In their data centres, priority is given towards the cooling of the servers as temperature is a vital aspect which ensures the optimal performance of these equipment.

TM's data centre employs an air driven cooling approach to cool the servers. Instead of opting for the overhead cooling method where cool air is distributed from the top to cool the equipment at ground level, TM went for the raised floor approach that relies on perforated tiles to deliver cool air from ground level to the server aisles. The air circulation pattern will be different for these two methods due to the direction of the airflow.

Another factor that influences the performance of the cooling scheme is the positioning of the server racks. TM's data centre has a strategic placement of these racks by segregating the aisles into hot and cold regions. Hot aisles are where the heated air is dissipated, and cold aisles are where the cool air is distributed. By placing these two aisles apart, the amount of cool air that is exposed to the hot air recirculation can be reduced.

Based on the server racks positioning done by TM, a higher temperature distribution is apparent at the lower part of the server racks. Several possibilities are that the quantities of the computer room air conditioner (CRAC) are not adequate to cool the data hall and hot air is concentrated at certain spots implying the existence of air stagnation.

1.2 Problem Statement

Data centres operate continuously because the equipment contained in these facilities are always running to provide the needed service to its clientele. To accomplish the highest levels of productivity, interruptions must be avoided. As these servers are in constant operation, lots of heat tend to be generated by the inner components that lead to higher operating temperatures. When the servers surpass the operating temperature threshold, it can overheat and cause the servers to go down for an indefinite period.

For optimal performance of data centres, the surrounding temperature of the servers need to follow the regulatory standards set by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Based on the equipment environment specifications outlined by ASHRAE, the allowable temperature range is 15 – 32 ^{o}C and 18 – 27 ^{o}C is the recommended temperature range (ASHRAE, 2011).

TM's data centre 3 logged high temperatures that were close to the allowable temperature limit at the lower section of the server rack. This leads to the hot air being in recirculation and influencing the temperature of the cool air in distribution. On the upper section of the server racks, the temperatures are on the lower side which indicates that the heat distribution is concentrated on the middle to lower sections of these racks.

To analyse the temperature distribution at TM's data centre 3, a computational fluid dynamics (CFD) study can be carried out. This method will be able to produce a temperature distribution plot that gives an in depth look at the data centre on the heat scale. By exploring the CFD output, occurrences of air stagnation and air recirculation, if any, can be ascertained. Based on this, constructive recommendations can be given to enhance the cooling effectiveness of the data centre.

1.3 Aim

The aim of this research project is to emulate and assess the cooling system utilized at TM City's data centre 3.

1.4 Objectives

For the aim to materialize, the following objectives need to be fulfilled:

a. To design and simulate the data centre's airflow and thermal distribution.

b. To determine the average temperature, concentrated hotspots, and hot air recirculation occurrence in the data centre.

c. To propose proper techniques to improve the cooling effectiveness of the data centre.

1.5 Scope of Research

As high temperatures that were close to the maximum allowable temperature were recorded at TM's data centre 3, this trend will be analysed by creating a three-dimensional model of the data centre prior to it being simulated using a CFD package. The simulation output will be studied, and necessary recommendations will be suggested to boost the cooling efficiency.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Data centre cooling system is crucial in ensuring a proper air distribution to cool the servers and appropriate thermal management to avoid any cases of overheating of servers. With changing times, newer servers with higher specifications will pressure the initial cooling system as it will dissipate more heat. Current literature of data centres with attention to airflow management will be analysed to understand the different views of authors on coming up with a practical cooling system for data centres. The findings are encapsulated according to its role in cooling below.

2.2 Floor Classification

There are two main types of flooring used in data centres, which are hard floors and raised floors. The layout for both these designs are different as various factors need to be considered.

2.2.1 Hard Floor

The type of floor that has no depth included in its build is known as a hard floor. Data centres that utilise this floor have the data cabling running in overhead cable trenches and the power cabling is positioned in cable trenches or delivered through a busway (Rasmussen, 2014). From this, the amount of headroom available must be enough to accommodate all the fittings to be installed. The author goes on to add that cool air distribution is normally done through a hanging ceiling return to the CRAC with vented ceiling tiles. He also adds that this approach will produce an output equivalent to a raised floor while being more cost-effective.

2.2.2 Raised Floor

A floor that possesses an increased height from the finished floor level is regarded as a raised floor. As opposed to the layout of a hard floor, the space located below the raised floor serves functions such as delivery of cool air to the servers, housing for ground grid, provides space for refrigeration pipes and chilled water, and as a place to run cables for power and data (Rasmussen, 2014). He stated that the costs associated with the installation of a raised floor is around RM 953 per m^2 but, this estimate does not consider the fees incurred to install power and data cables. This statement shows that the total cost involved in constructing a raised floor data centre is significant and can climb further if more features are to be added.

From Figure 2.1, the raised flooring is made up entirely of tiles. This makes the server racks arrangement flexible because the tiles are interchangeable which makes it easy to accommodate any layout changes.

Figure 2.1: Raised floor used in data centres (Primefloor, 2018)

2.3 Containment

The environment in a data centre is a mixture of hot air exhausted from the server outlets and cold air distributed to the server inlet for cooling purposes. To maintain the cooling efficiency, the server racks are segregated according to server positioning, where areas in front of the server inlets are cold isles and the area facing the server outlets are hot isles. Containment is a method to contain the hot/cold air within its own boundary to prevent the blending of these two types air because it lowers the efficiency of the data centre in terms of temperature management.

2.3.1 Cold Aisle Containment System (CACS)

An enclosure that covers the cold aisle portion is the CACS. This system makes the entire room become a hot air return plenum by encasing the cold air within its boundary as shown in Figure 2.2 (L). Niemann et al. (2011) mentioned the temperature of the area without containment will match that of the hot aisle. This scenario will make it difficult for data centre personnel to perform their tasks. They also state that distinct arrangements such as a custom-made ducting that can pull cool air from the cold aisles, are needed for items that are not racked such as storage units. This helps the equipment to perform as intended despite the higher temperatures.

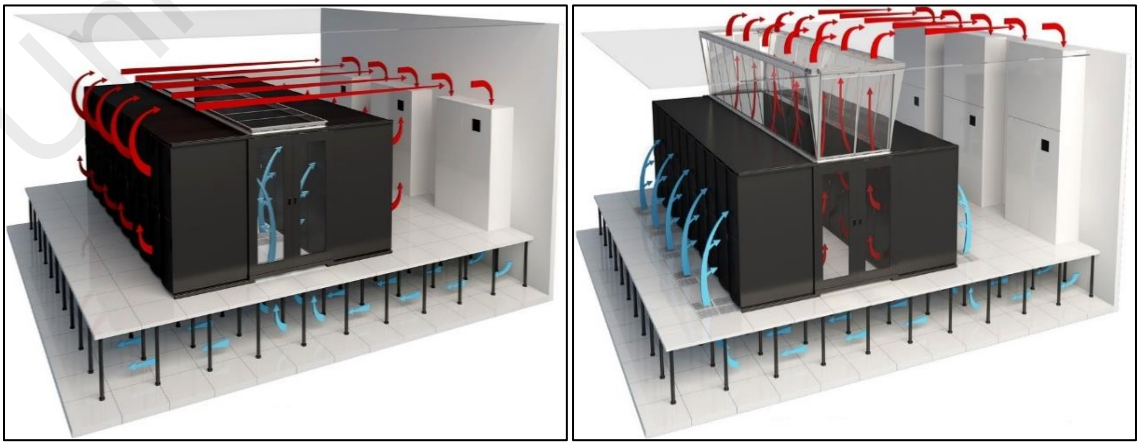

Figure 2.2: Cold aisle (L) & hot aisle (R) containment systems (Technologies, n.d.)

2.3.2 Hot Aisle Containment System (HACS)

The hot aisle that is enclosed to keep the hot air from escaping is known as HACS. Figure 2.2 (R) depicts the data centre becoming a cold air plenum due to the hot aisle being sealed off from the rest of the data hall and the hot air being returned to the CRAC via an overhead duct. The usage of economizers is a benefit of the HACS implementation which allows for greater energy savings that are substantially better than CACS that employs economizers (Niemann et al., 2011). They mentioned that the vicinity outside the hot aisle will be cool like the cold aisle. They also asserted that HACS permits elevated temperatures of the hot aisles compared to CACS which is a major variation between both as HACS lets the CRAC units to function more effectively.

2.4 Computer Room Air Conditioning Configuration

CRAC is a critical component within a data centre configuration. It is tasked with cooling the entire data hall efficiently to prevent malfunctions to the information technology (IT) equipment. The number of CRAC units needed for each data centre varies as it depends on the cooling requirement of the servers. When the cold air is disseminated through the perforated tiles, the servers situated at the lower region will be exposed more and the servers situated at the higher region will possibly be getting the hot air that is in recirculation (Nada & Said, 2017). They noted that hot air recirculation can cause hot spots in servers as it elevates the intake air temperature of the servers placed at the upper part of the rack and this indirectly leads to servers positioned at the bottom to be cooled more than the required level which is a surplus of cooling energy. Their research suggests that the layout of CRACs play an important part in the cooling of a data centre because CRACs placed at right angles to the server racks line improved the air stream homogeneity from the perforated tiles along the rack line, and hot air recirculating and cold air bypass can be minimized.

2.5 Cooling Performance Indices

A data centre's total cooling performance can be measured by using the appropriate indexes. Sharma et al. (2002) researched the factors that influenced the thermal performance of a data hall. The main factors they investigated were the impacts ceiling height and width of the aisles. The study indicated that the cooling of data centres can be altered in diverse methods relying on its existing framework by applying dimensionless parameters, Supply Heat Index (SHI) & Return Heat Index (RHI). The study also noted that a ceiling structure model that was analysed in terms of heat load showed that data centres' functionality can be enhanced by both, heat loads and dimensional parameters.

In a perfect situation, the CRAC distribution temperature should be identical to the rack inlets' temperature. Nevertheless, this is not the case as hot air in recirculation will enter the cold isle into the rack inlets and due to this, the efficiency will decline. The indices of SHI and RHI are in place to examine the effects of the recirculating hot air. These indices are in relation to the temperatures of the rack inlet, rack outlet and distributed air. For SHI, the dividend signifies the heat collected in the cold aisle prior to accessing the racks and the divisor embodies the overall heat collected by air exiting the racks. RHI assesses the amount of heat removed by the CRAC sections corresponding to the heat absorbed by the airflow while leaving the rack. In a restricted system that is free of seepage to the surroundings, unity is attained when SHI and RHI are tallied (Chu & Wang, 2019).

An additional performance metric is known as the Rack Cooling Index (RCI). It represents the connection between temperature of the rack inlet to its permissible and suggested limits for a ceaseless functionality of the data centre. Over-temperature is when the highest proposed server intake temperature is surpassed. Under-temperature is the server intake temperature is beneath the lowest suggested. 91 – 96% is an acceptable operation range and anything below 91% is a poor operation range for the high RCI intended for over-temperatures. Low RCIs which deals with under-temperatures act as an accompaniment to high RCIs, particularly when the distribution condition is lower than the minimal proposed temperature (Nada et al., 2016).

2.6 Meshing

Meshing is a vital aspect of CFD simulations. Mesh is the process of breaking down intricate geometries into unsophisticated components. The mesh accuracy is a crucial factor that influences the precision of the results obtained (ANSYS, 2014). The author also underscored that there are a range of mesh characteristics such as nature of mesh and median of mesh size that can be altered to achieve a higher degree of simulation outcomes.

Various types of mesh are available for simulation purposes. Each type of mesh has its own attributes that will affect the solution accuracy. According to a review done by Sadrehaghighi (2020), complex geometries should employ tetrahedral meshing and simple geometries should utilize hexahedral meshing. The review stresses that hexahedral meshing will take a longer time at the meshing phase, but it computes at a faster pace which is particularly helpful if the model is to be recalculated several times. In contrast, the review also highlighted that, tetrahedral meshes are quick at the meshing phase, but slower at the computational stage which translates to the need for higher computing power.

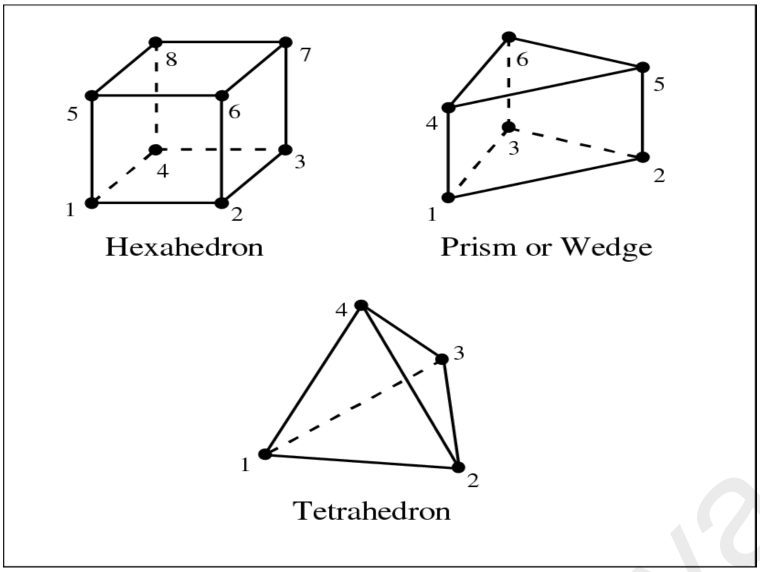

Figure 2.3: Common three-dimensional cell shapes (Lin et al., 1997)

2.7 Mesh Quality Metrics

Meshing quality can be gauged by examining the metrics pertaining to it. The quality of the mesh plays a role in the convergence of the solution. There are many parameters such as parallel deviation, jacobian ratio, characteristic length and etc that can be used to test the mesh quality. For this study, the critereons chosen to examine the mesh quality are skewness and orthogonal quality.

Ozen (2014) stated that skewness is the deviation of the element in comparison to its perfect form. On the skewness mesh metrics spectrum as shown in Table 2.1, values ranging from 0 to 0.94 are acceptable and values from 0.95 to 1 are unacceptable.

Table 2.1: Skewness mesh metrics spectrum

Excellent	Very good	Good	Acceptable	Bad	Unacceptable
0-0.25	0.25-0.50	0.50-0.80	0.80-0.94	0.95-0.97	0.98-1.00

(Ozen, 2014)

According to Ozen (2014), orthogonal quality is described as the closeness of optimum angles to the angles between adjoining cell faces. Based on Table 2.2, the orthogonal quality mesh metrics spectrum implies that values in the range 0 to 0.14 are generally unfavourable, while values ranging from 0.15 to 0.95 are encouraging and values between 0.95 to 1 is rated as excellent.

Table 2.2: Orthogonal quality mesh metrics spectrum

Unacceptable	Bad	Acceptable	Good	Very good	Excellent
0-0.001	0.001-0.14	0.15-0.20	0.20-0.69	0.70-0.95	0.95-1.00

(Ozen, 2014)

The desired mesh quality metrics can be achieved by applying the right meshing criterias which differ based on the complexity of the geometry. These mesh quality metrics can be found in the meshing component within the ANSYS software.

2.8 Mesh Independence Test

Meshing has various precision levels which are dependent on its settings. Mesh (or grid) independence can be achieved by running a series of tests, each with distinctive mesh sizing, which produces results that are identical, and the error margin is small enough to be neglected (Thompson et al., 1999). There are several factors that affect the mesh independence.

Firstly, the spacing is vital to mesh independence. For an agreeable degree of momentum and mass conservation to be maintained, the mesh should be adequately fine (Godderidge et al., 2006). The authors noted that the fine meshing requires the mesh size to be small which ultimately requires more computing power that will add to the overall cost. The authors also mentioned that mesh sizing needs to be altered based on the timestep when transient problems are studied as the mesh size and timestep should be equal in terms of its size, and the Courant number, known as the flow speed rate with which the arithmetical instabilities disseminate, dictates this technique.

Next, resolution influences the mesh independence. Flow resolving in the entire domain being computed will be effective provided that the mesh spacing is appropriately tiny (Wilcox, 2006). The author adds that this is particularly crucial when a turbulence modelling is employed, as the simulation quality largely depends on the location of the initial mesh point that is close to the wall. The author highlighted that characteristics of the regional stream are smudged if a coarse mesh is utilized.

In addition, mesh independence is affected by the geometry. The meshing must embody the geometry realistically (Godderidge et al., 2006). The authors highlighted that a surface's minor variations or specific traits of a body which influences the stream can be captured effectively provided the geometry is meshed precisely. The authors stated that care should be taken to ensure the simulation outcome is impartial of the mesh utilized because the meshing signifies the problem in terms of computation.

2.9 Reynolds Number

In the classification process of fluid techniques, a non-dimensional number known as Reynolds number is used to determine whether a flow is laminar or turbulent. It is the fraction of forces (inertial to viscous). The numerical method of evaluating the Reynolds number is (Rehm et al., 2009):

$$N_{Re} = \frac{\rho v d}{\mu} \tag{2.1}$$

The flow is classified as laminar if the Reynolds number equals 2100 or less. On the other hand, the flow is turbulent if the Reynolds number exceeds 2100. The laminar flow is steady while the turbulent flow is disorganized (Rehm et al., 2009).

2.10 Governing Equations

CFD is built on the basic prevailing fluid dynamics equations. These equations are assimilated into all CFD analysis.

2.10.1 Continuity Equation

It is the conservation of mass. According to Jr. et al. (2009), the conservation outline of the continuity equation is as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{V}\right) = 0 \tag{2.2}$$

2.10.2 Momentum Equation

This is founded on Newton's 2nd Law of motion. It states that force is the product of mass and acceleration. It is for a fluid element that is in motion. Based on the work of Jr. et al. (2009), the momentum equation is as follows:

$$\frac{\partial (\rho u)}{\partial t} + \nabla \cdot \left(\rho u \vec{V}\right) = \left[-\frac{\partial P}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z}\right] dxdydz + \rho \, . f_x \tag{2.3}$$

2.11 Turbulence Modelling

In CFD simulations, the user cannot precisely denote the influences of turbulence. Thus, a turbulence model is required. Different models will have different effects on the simulation results. To get the best results, the most accurate model needs to be chosen on a case to case basis. There are many available models such as k-epsilon (k-ε), k-omega (k-ω), and SST Transition. Among all the available models, the k-ε model is regarded as one of the most used turbulence models in the engineering field. There are three types of k-e models, namely Realizable k-ε, Renormalized Group (RNG) k-ε and Standard k-ε (ANSYS, 2010).

The k-ε model is a two-equation model whereby the result of two distinct transport equations lets the turbulent velocity and length scales to be autonomously resolved (ANSYS, 2013). In this research, the Realizable k-ε model was used. The derivation of the dissipation rate, ε is based on the mean-square vortex variation which is dissimilar compared to the standard k-ε model. One advantage of this model is the dispersion rate of planar and circular jets can be precisely foreseen. For flows that include rotation, separation and recirculation, this model performs at a higher level in contrast to the standard k-ε model (ANSYS, 2010). The realizable k-ε model consists of two transport equations which denote the flow's turbulent properties and these equations are (ANSYS, 2013):

(i) Turbulent kinetic energy, k

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}\left(\rho k u_j\right) = \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_k})\frac{\partial_k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \tag{2.4}$$

(ii) Turbulent dissipation rate, ε

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_j}\left(\rho\varepsilon u_j\right)$$
$$= \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_\varepsilon})\frac{\partial_\varepsilon}{\partial x_j}\right] + \rho C_1 S\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{v\varepsilon}} + C_{1\varepsilon}\frac{\epsilon}{k} C_{3\varepsilon} G_b + S_\varepsilon \tag{2.5}$$

where;

$$C_1 = \max\left[0.43, \frac{\eta}{\eta + 5}\right]$$

$$\eta = S\frac{k}{\varepsilon}$$

$$S = \sqrt{2S_{ij}S_{ij}}$$

The model constants have been determined to make certain that the model works well for particular canonical flows. They have the following pre-set values:

$$C_{1\varepsilon} = 1.44 \quad C_2 = 1.9 \quad \sigma_k = 1.0 \quad \sigma_\varepsilon = 1.2$$

2.12 Summary of Literature Review

The purpose of this review was to understand the elements that influenced the cooling aspect of a data centre. It is evident from the literature reviewed that the airflow management is very critical to the cooling and heating of a data centre as it is the medium which transports cold and hot air within the boundary of the servers. Also, the computational aspects of this research such as meshing, and turbulence modelling play a major part in attaining accurate CFD simulation results. Hence, there is a need to pay attention to detail when it comes to these attributes as the closer the computational modelling is to the actual geometry, the results obtained will be more authentic. From the studies conducted, all the highlighted areas above must be addressed accordingly to achieve the desired outcomes that are identical to an actual data centre environment, at the end of this research study.

CHAPTER 3: METHODOLOGY

3.1 Introduction

The methodology describes the details of the data centre design and analysis comprehensively. The experimental design is used as a model for the computer aided drawing (CAD), which is then analyzed via CFD simulation. The initial and CACS setups are expounded in terms of the meshing, boundary conditions and setup options used for the CFD simulation.

3.2 Research Project Process

There are many phases involved in the overall completion of a research project. Every phase is crucial in providing the right information needed to proceed to the next stage. Figure 3.1 shows these stages from start to finish.

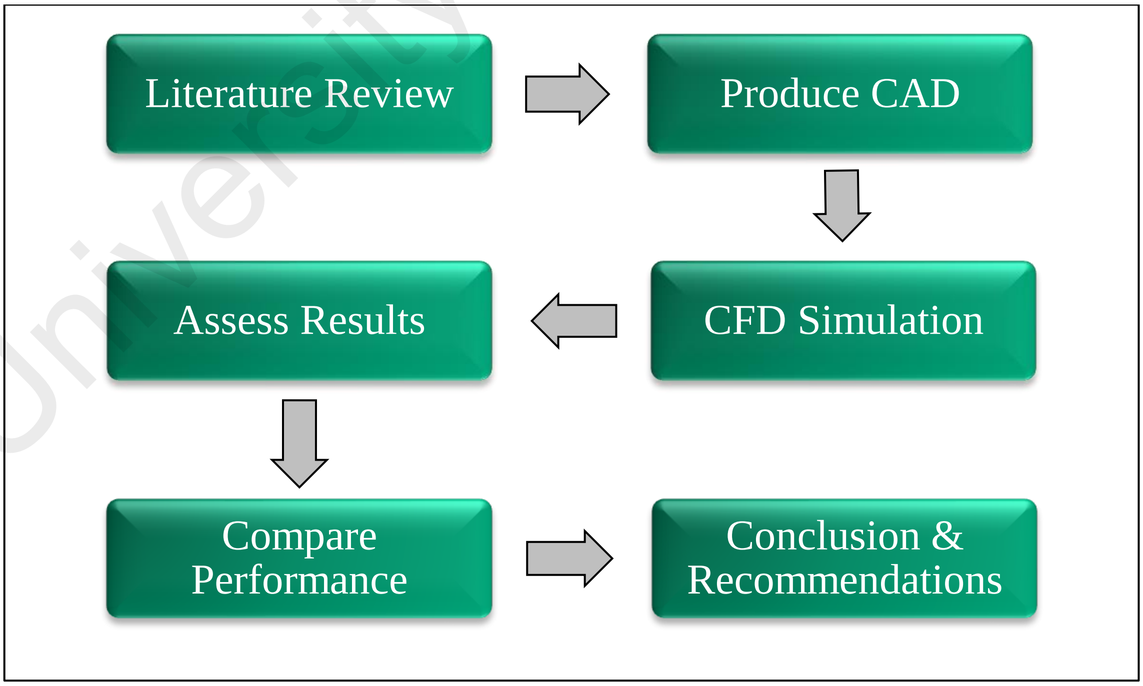

Figure 3.1: Methodology flowchart

3.3 Geometry Modelling

The experimental design is TM City's data centre 3. It is made up of 43 server racks, 2 remote power panels (RPP), a total of 3 CRACs, in which only 2 are active, and 43 air grills. The design follows TM City's data centre 3 outline as shown in figure 3.2 except for the server racks and air grills, as these two entities are designed collectively without compartmentalizing each unit individually. The server racks arrangement is divided into single and double aisle configuration that are further segregated to hot and cold regions. The CRACs provide cool air to the servers via a cool air inlet that is hidden within the confines of the raised floor. The dimension of this data centre is 12m x 8m x 4.75m.

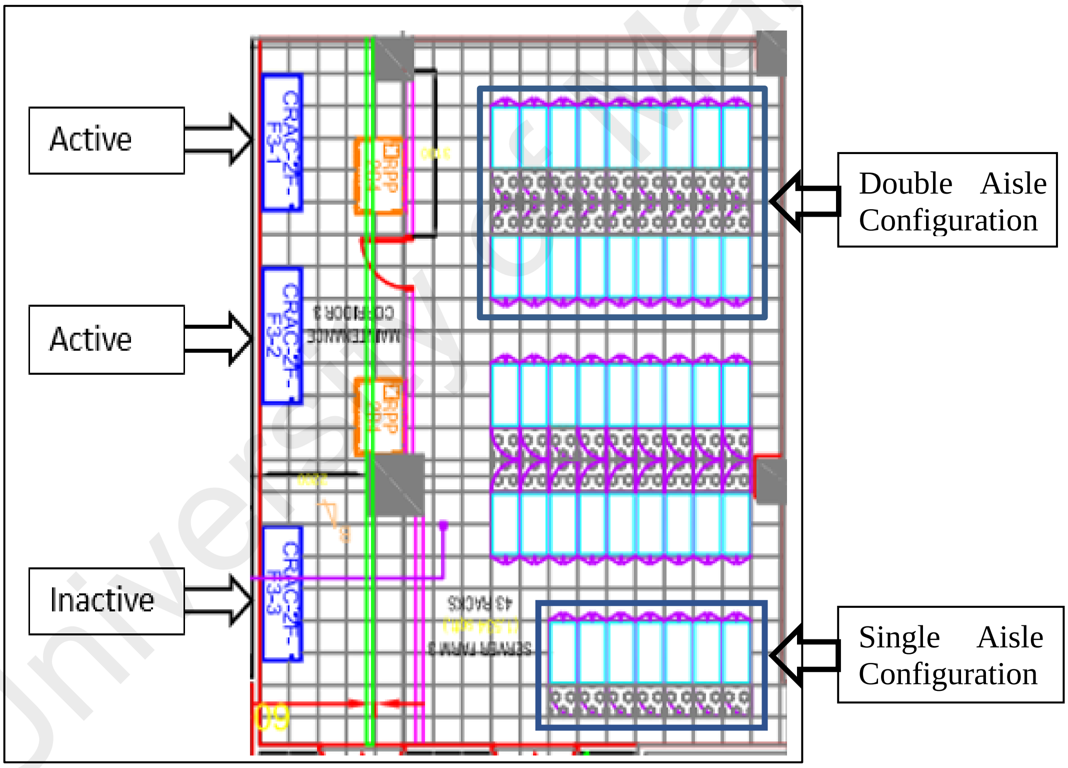

Figure 3.2: Layout of TM City's data centre 3

Figure 3.3 shows the data centre that has been designed using SolidWorks 2018. A black box modeling approach was utilized during the design phase. This method relies on a component's boundary conditions as an alternative to flow modeling within it (Wibron et al., 2016). The airflow inside the data centre and over the components are resolved, but airflow within the server racks, CRACs and area below the raised floor are not resolved. The components are presumed to be rectangular boxes because of the resemblance to its physical state. External fittings such as lighting and cabling are omitted from the design.

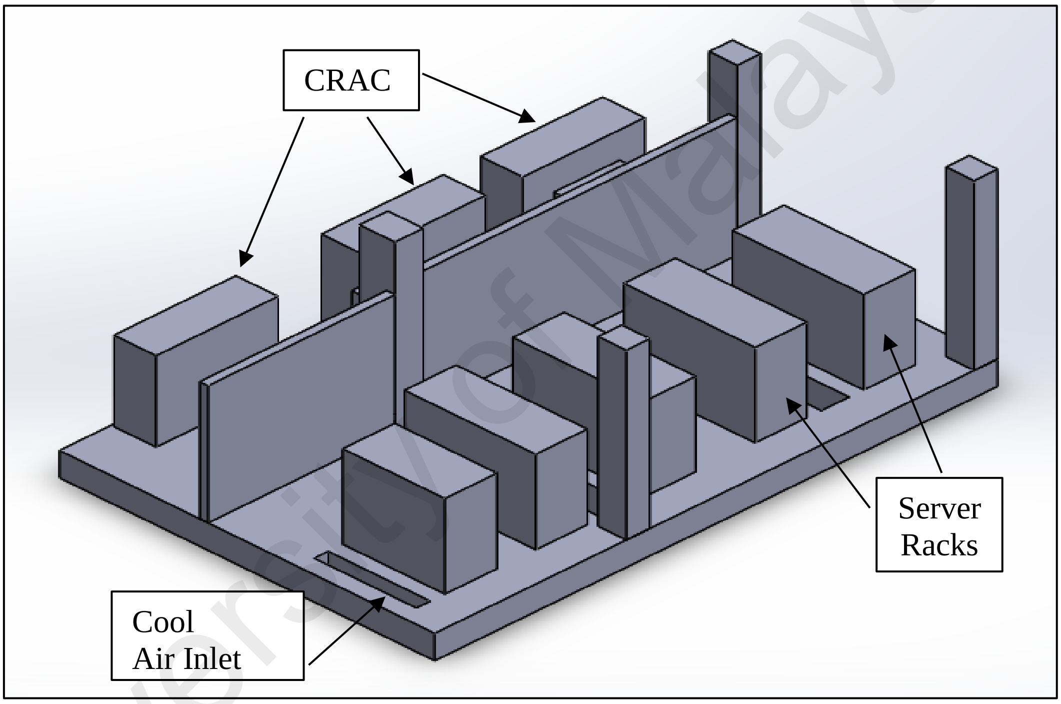

Figure 3.3: CAD model of TM City's data centre 3 based on the initial setup

The CAD model is then imported into a CFD software, ANSYS, for analysis. The first step taken was to execute the DesignModeler sub-product to adapt the CAD model into the CFD environment. Here, a bounding box is created to surround the entire geometry. Then, the Boolean operation was used to subtract the geometry from the bounding box that creates a fluid domain in which the simulation takes place.

Figure 3.4 depicts the geometry that has been processed using DesignModeler and is applicable for CFD operations. The gaps are the result of the Boolean operation that removed the overlapping portion of objects from a set of base objects. In this phase, there are a selection of operations such as patterns and body transformation that can influence the design output, hence research and understanding is needed to accurately execute the right options to create the design that is identical to the physical model. This geometry is then processed using the Meshing sub-product to create a meshed output.

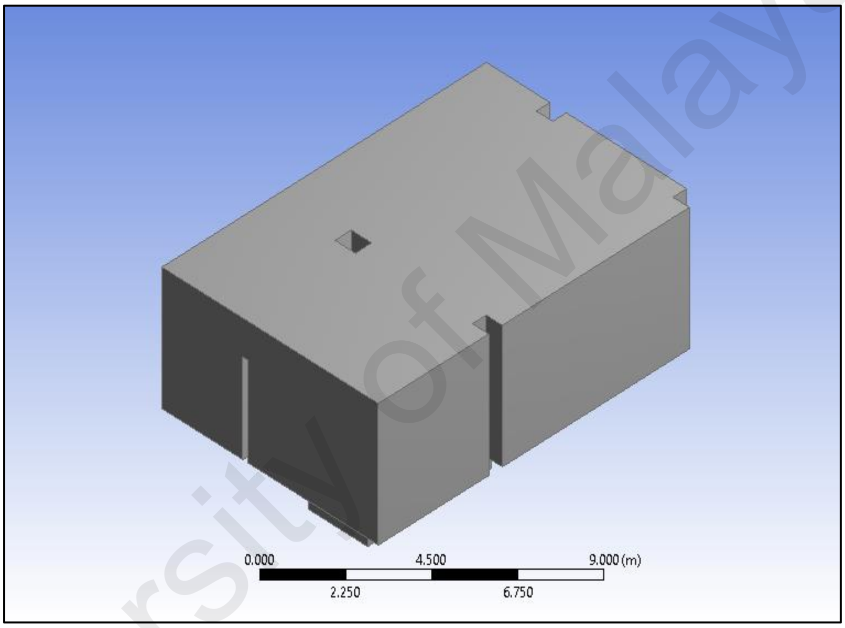

Figure 3.4: Data centre geometry post fluid domain creation

3.4 Geometry Meshing

The geometry is meshed to make the design simpler by dividing it into fundamental segments. The meshes are generated by the software based on the user's input that varies depending on the complexity of the design. The mesh created should embody the geometry modeled with high accuracy. This is achieved by producing the right number of exceptional cells.

The meshing illustrated in figure 3.5 is the result of the mesh generated for the entire data centre. As the geometry is quite straightforward, the hexahedral meshing was employed because it computes at a faster pace despite the meshing phase taking slightly longer to process. The mesh sizing was altered by using the body sizing option that allows the user to tweak the element size of the cells. The element sizes ranging from 0.6m to 0.1m were analysed to choose the most appropriate mesh sizing for the geometry. The chosen element size was 0.1m and the results of this mesh independence study will be elaborated in detail in the results section.

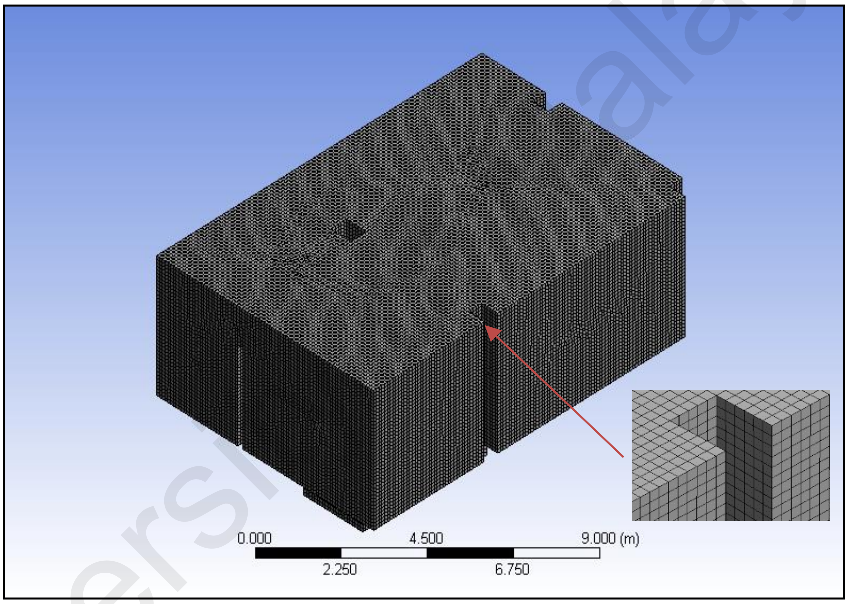

Figure 3.5: Meshed data centre with a magnification of the meshing

This mesh contains 365,013 nodes and 368,385 elements. The total number of nodes and elements are dependent on the element size as the geometry will be broken down into more elements as its size decreases, consequently creating more nodes that connect these elements. Another mesh feature considered is the mesh aspect ratio. The value of the aspect ratio is kept closest to 1 to ensure the cells are not overly stretched as the ratio is obtained by dividing the values of the maximum and minimum cell centroid and nodes.

Subsequently, the mesh quality metrics were evaluated by focusing on skewness and orthogonal quality.

From table 3.1, the average mesh skewness is 0.13642. By referring to table 2.1, this skewness falls under the excellent category. Conversely, the average orthogonal quality of the mesh is 0.91163 based on table 3.1. This orthogonal quality is very good as denoted in table 2.2. Mesh metrics should be used as a yardstick towards achieving a converged solution. However, these mesh metric classifications do not guarantee that convergence can be achieved, because even a miniscule localized mesh problem can steer the solution towards divergence.

Table 3.1: Mesh metrics of initial setup – skewness & orthogonal quality

Mesh Metric	Skewness
Min	3.8202e-010
Max	1.
Average	0.13642
Standard Deviation	0.21804

Mesh Metric	Orthogonal Quality
Min	1.6509e-007
Max	1.
Average	0.91163
Standard Deviation	0.21368

3.5 Boundary Conditions

Among the steps involved in outlining boundary conditions are determining the boundary locations and providing the right data at these boundaries. Common boundary locations are walls, inlets, and outlets. The data that is provided at the boundaries vary depending on the physical geometries. The accuracy of the solution is highly reliant on the information set at the boundary conditions.

In this research, the data centre's ceiling, flooring, and walls are presumed to be adiabatic. This translates to there being no heat energy entering or leaving the data centre. An assumption that air leakage does not occur through the components and data centre itself is made. The heat transfer phenomenon within the data centre is modelled using thermal energy. The boundary condition locations as illustrated in figure 3.6 were set in the meshing component using the named selections option.

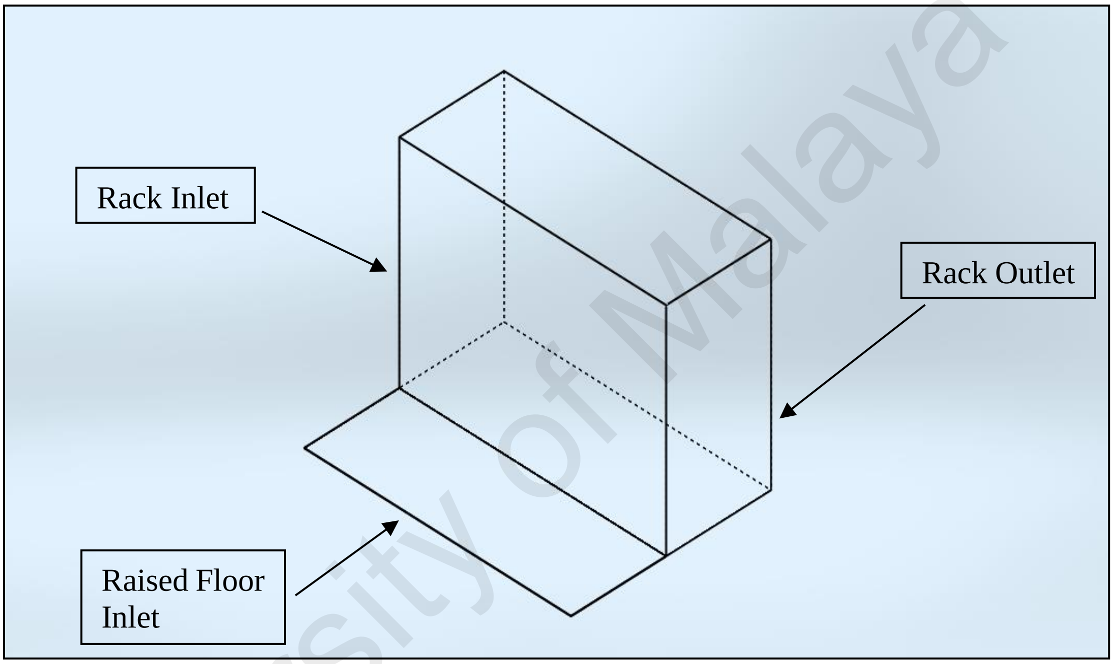

Figure 3.6: Boundary conditions of a server rack

Several assumptions were made with regards to certain boundary conditions input values because the data was not available. Each server rack was set to generate a heat load of 3 kW and its internal fan was set to produce airflow at a rate of 0.56 m/s. According to a research done by Wibron et al. (2016), a temperature difference as high as 7 ^{o}C between the front and back of the servers occurs due to the heat load. The other boundary conditions and relevant inputs will be tabulated in the setup section.

The initial setup of TM City's data centre 3 is a normal data centre that deals with the issue of hot air recirculating from the hot aisle that mixes with the cool air in the cold aisle. The blending of these two types of air leads to a higher air inlet temperature in front of the server racks. As a countermeasure, a cold aisle containment that segregates the cold air from the hot air, was added to the existing data centre. An appraisal on the efficacy of this enclosure method is performed as well.

3.6 Cold Aisle Containment System Layout

The data centre model equipped with the CACS is shown in figure 3.7. The purpose of the panels enclosing the cold aisles is to avoid the cold air from mixing with the hot air that is in recirculation.

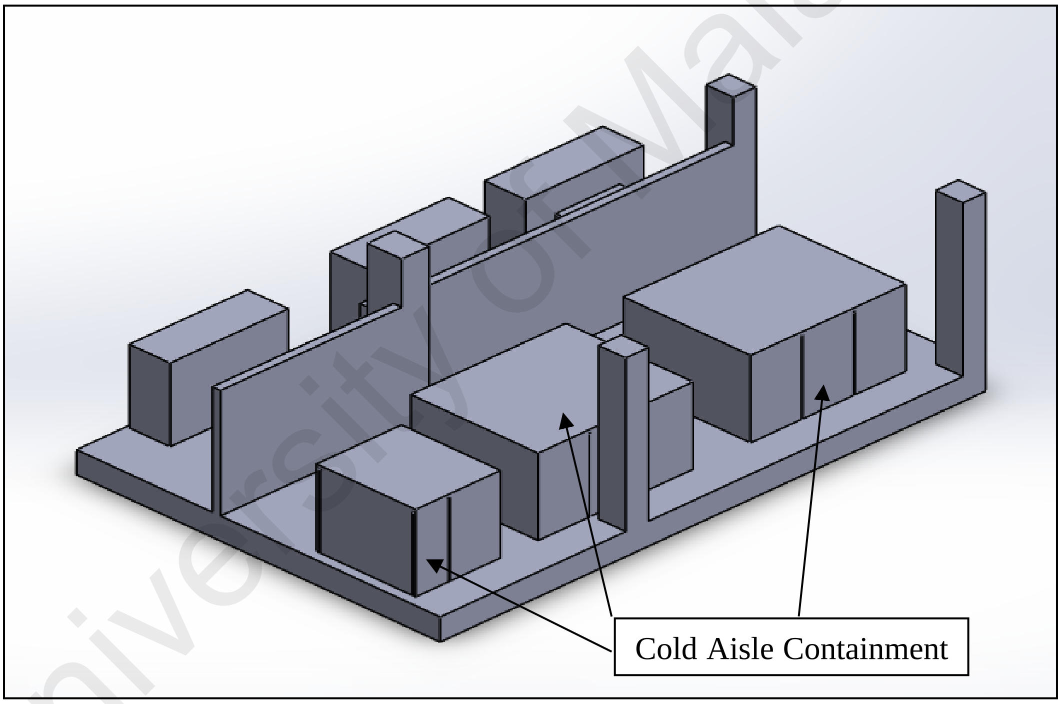

Figure 3.7: CAD model of TM City's data centre 3 with CACS installed

Figure 3.8 depicts the meshing of the data centre equipped with the CACS. All the meshing options used are identical to the initial geometry, to evaluate the results consistently. The hexahedral mesh with an element size of 0.1m was used. This meshing contains 368,758 nodes and 370,282 elements. This CACS equipped data centre mesh has more nodes and elements in contrast to the mesh of the initial setup. This difference is due to the meshing of added panels in the CACS setup.

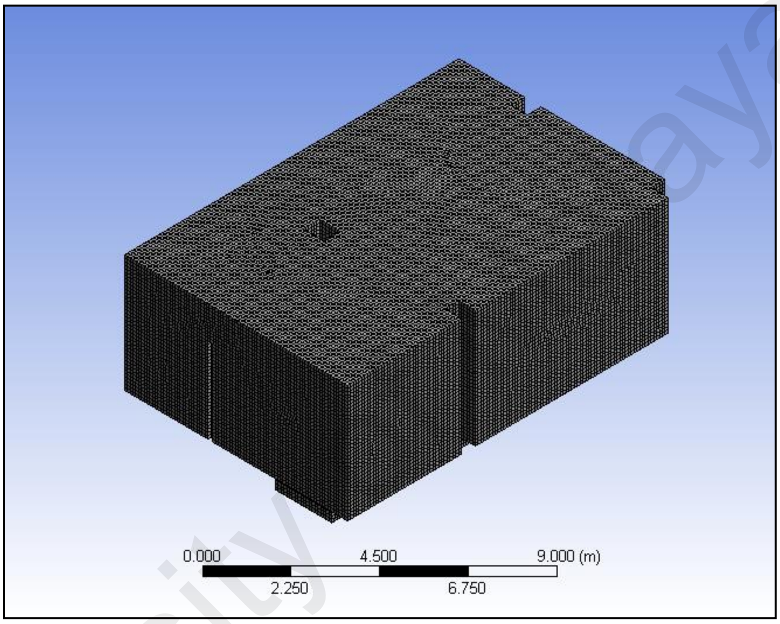

Figure 3.8: Meshed data centre with CACS

The average mesh skewness is 0.14365, from table 3.2. By referring to table 2.1, this skewness comes under the excellent category. Correspondingly, based on table 3.2, the average orthogonal quality of the mesh is 0.90857. This orthogonal quality is very good as shown in table 2.2.

Table 3.2: Mesh metrics of CACS setup – skewness & orthogonal quality

Mesh Metric	Skewness
Min	3.3929e-009
Max	0.99999
Average	0.14365
Standard Deviation	0.22034

Mesh Metric	Orthogonal Quality
Min	1.223e-005
Max	1.
Average	0.90857
Standard Deviation	0.2147

3.7 Setup Phase

This phase is the most important as the input values, setting of the boundary conditions and type of modelling to be used in the calculations are all done in this module. There are many options to choose from for each parameter related to the modelling. Therefore, by understanding how the physical model performs in real world situations, then only can the simulation settings be input to mimic its performance precisely. The settings used for the CFD simulations are listed down in table 3.3.

Table 3.3: Settings applied for CFD simulations in ANSYS Fluent

No.	Item	Parameter	Input
1	General	Solver	Pressure based
		Velocity Formulation	Absolute
		Time	Steady
		Gravity	-9.81 ms^{-2} (Y direction)
2	Models	Energy	On
		Viscous	Realizable k-ε (2 equations) with standard wall functions
		Others	Off
3	Materials	Fluid	Air
		Solid	Aluminium

No.	Item	Parameter	Input
4	Cell Zone Conditions	Fluid	Solid zone Material: air
5	Boundary Conditions	Air Grille Inlet	Velocity: 1.12 ms^{-1} Temperature: 20 ^oC
		Rack Inlet	Pressure: 0 Pa Temperature: 25 ^oC
		Rack Outlet	Velocity: 0.58 ms^{-1} Temperature: 30 ^oC
		CRAC Inlet	Pressure: 0 Pa Temperature: 25 ^oC
		Server Walls	Stationary Wall Convection: 3 kW
		CRAC Walls	Stationary Wall Convection: 3 kW
6	Reference Values	Compute From	Air Grille Inlet
		Reference Zone	Solid
7	Methods	Pressure-Velocity Coupling	Coupled
		Gradient	Least Squares Cell Based
		Pressure	Second Order
		Momentum	Second Order Upwind
		Energy	Second Order Upwind
8	Initialization	Method	Hybrid Initialization
9	Run Calculation	Number of Iterations	1000

CHAPTER 4: RESULTS & DISCUSSION

4.1 Introduction

The results obtained from the mesh independence study and CFD simulations are presented in this chapter. The results will provide a basis for comparison between the data centre's initial and CACS setups. Based on these results, the conclusion and recommendations will be imparted in the next chapter.

4.2 Mesh Independence Study

The mesh independence study analyses 6 different element sizes for both the initial and CACS geometry setups. All the parameters were kept constant. The particulars of these meshes are presented in tables 4.1 – 4.2. The mesh elements and nodes are inversely proportional to the element size. Table 4.1 shows the varying mesh statistics of the initial setup. The temperature value has an error of less than 1% for mesh number 6. This shows that the solution value is impartial of the mesh resolution.

From table 4.2, the mesh statistics for the data centre equipped with CACS are shown. The temperature values have a minimal distortion for all meshes except for mesh 3 with a drastic decline that produced a very high error percentage. However, the temperature values were steady with finer meshes being used. Mesh independence was reached at mesh 6 where the error was below 1%. Refined meshes show a higher tendency towards mesh independence. For both cases, an element size of 0.1m were utilised based on the outcome of the mesh independence study conducted.

Table 4.1: Mesh statistics of the initial geometry setup

Mesh No.	Element Size [m]	Mesh Nodes	Mesh Elements	Total Temperature [^oC]
1	0.6	3283	3813	25.11
2	0.5	4576	4797	25.16
3	0.4	8281	8195	24.72
4	0.3	17808	17071	24.38
5	0.2	51625	52719	24.48
6	0.1	365446	367465	24.34

Table 4.2: Mesh statistics of the CACS geometry setup

Mesh No.	Element Size [m]	Mesh Nodes	Mesh Elements	Total Temperature [^oC]
1	0.6	3507	4350	29.03
2	0.5	5081	5944	28.73
3	0.4	8926	9658	-59.86
4	0.3	18660	18961	29.31
5	0.2	53250	54859	29.37
6	0.1	369134	372022	29.44

4.3 Simulation of Data Centre

Based on temperature contours at the server racks' inlets as shown in Figure 4.1, the temperature varies at different locales between the ranges of 20.57 ^oC to 29.79 ^oC with an average of 25.18 ^oC. The maximum temperature recommended by ASHRAE's data centre thermal guidelines is 27 ^oC, indicating that the server racks' inlet highest temperature is closer to the maximum allowable temperature of 32 ^oC. Hence, cooling reinforcements are required to improve the cooling efficiency of the server racks.

The temperature is lower at the bottom portion of the server racks and in contrast, higher on the upper region of the server racks. This is due to the cool air being supplied from the bottom which makes the lower portion of the racks more prone to be cooled. On the other hand, as this cool air encounters the hot surface of the server walls, the air becomes warmer and less dense which makes it move toward the upper portion of the server racks. Next, the sides of the server racks are showing higher temperatures. As this unenclosed setup provides no segregation between the hot exhaust air and the cool air, the hot air tends to travel to the front portion of the server racks, and this leads to the temperature increase at the side of these racks.

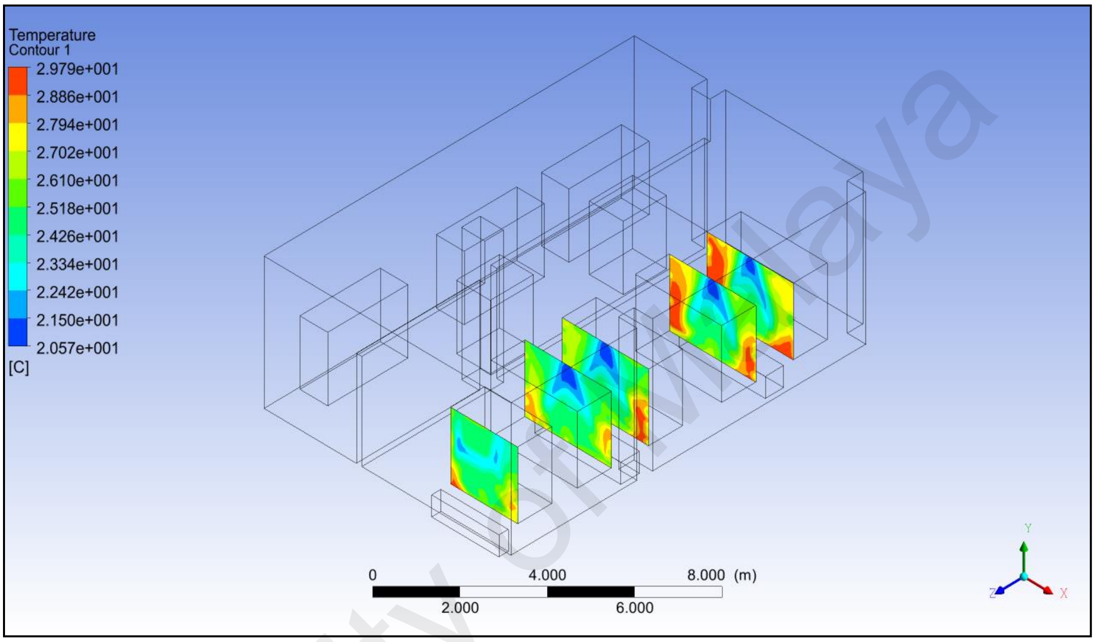

Figure 4.1: Temperature distribution at the server racks' inlets

The velocity streamlines in figure 4.2 illustrate the phenomenon of exhaust air recirculation. The hot air from the hot aisles tend to recirculate back into the cold aisles. The velocity of the air increases as it encroaches the cold aisles. This is expected because of the internal fans housed within the server racks. These fans produce a suction force that can pull the exhaust air that is recirculating towards it.

Figure 4.2 also shows the hot air flowing above the wall partition into the return air inlet on the CRAC units. It is observed that the exhaust air flows toward 2 of the active CRAC units and there is no airflow detected near the inactive CRAC unit. The hot air is then condensed and returned into the data centre as cool air for cooling purposes.

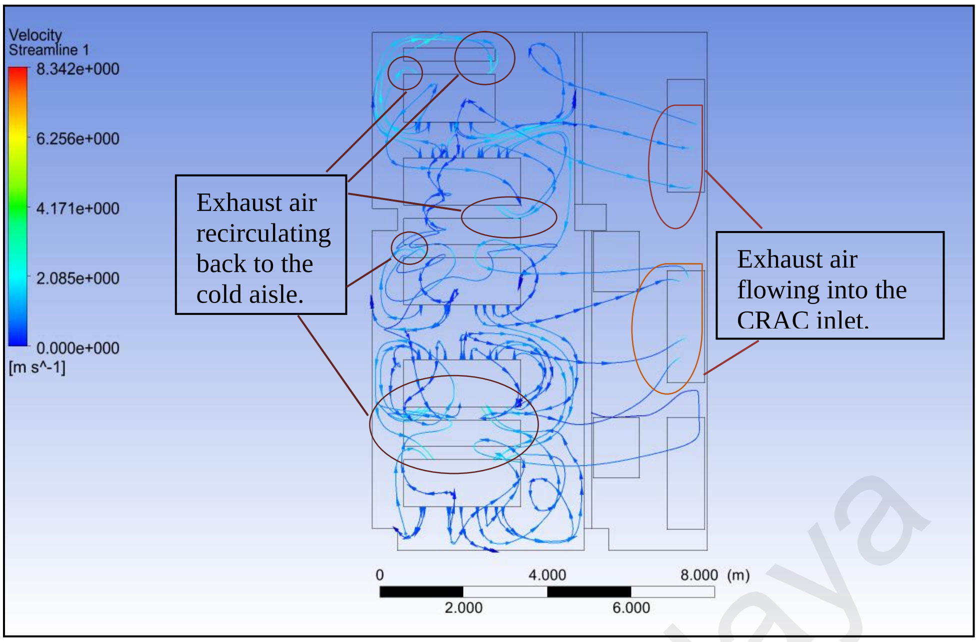

Figure 4.2: Exhaust airflow streamlines across the data centre

The heat dissemination within a data centre can be further analysed by evaluating the thermal contours at various altitudes. These contours are located on horizontal planes at the floor level (0.1 m), mid-rack level (1.05 m) and top of rack level (2.09 m) as shown in figure 4.3. These contours were analyzed at different altitudes to observe the effect of the heat from the exhaust air on the cold air supplied for cooling purposes.

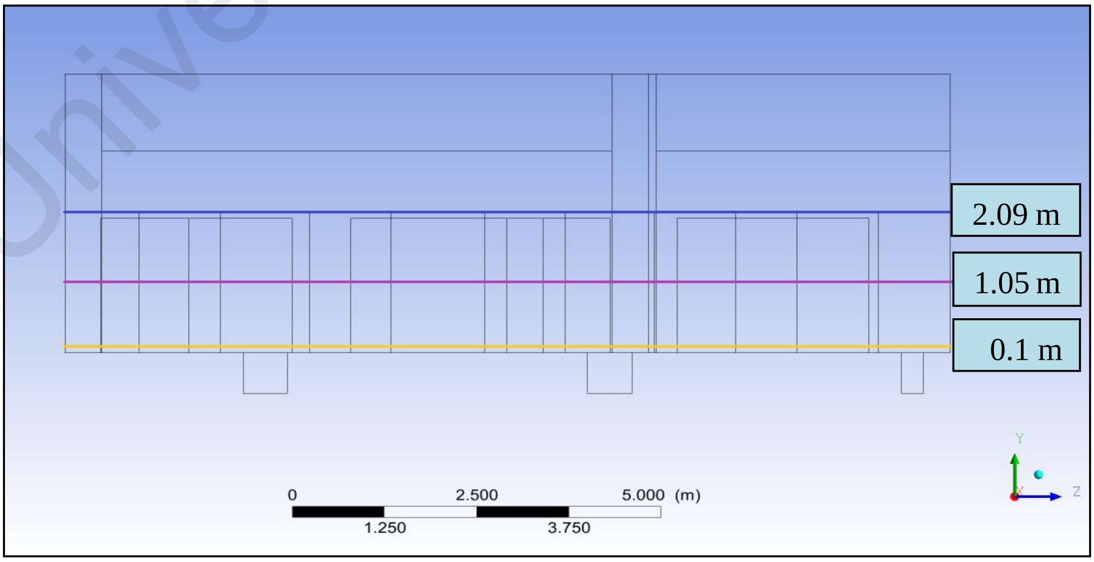

Figure 4.3: Horizontal planes located at different levels of server racks

Figures 4.4 – 4.6 illustrate the temperature contours at various heights. As shown in figure 4.4, at the floor level, the cold aisles are largely cooler, the sides of the racks are hot and the M&E room is warm at 26.01 ^{o}C. In contrast, the hot aisles and its surroundings areas are at the maximum temperature of 30.03 ^{o}C. At the mid-rack level, it is observed from figure 4.5, that the cool portion in front of the server racks have shrunk and there is a reduction of heat at the side of the racks with bigger warm air segments. At the top of the rack level depicted in figure 4.6, most areas in the data centre have a relatively higher air temperature ranging from 23.66 ^{o}C to 32.33 ^{o}C and only small segments of cool air present at an average of 21.93 ^{o}C. This implies that only a limited amount of cool air reaches a higher elevation as its portion shrinks with altitude increase.

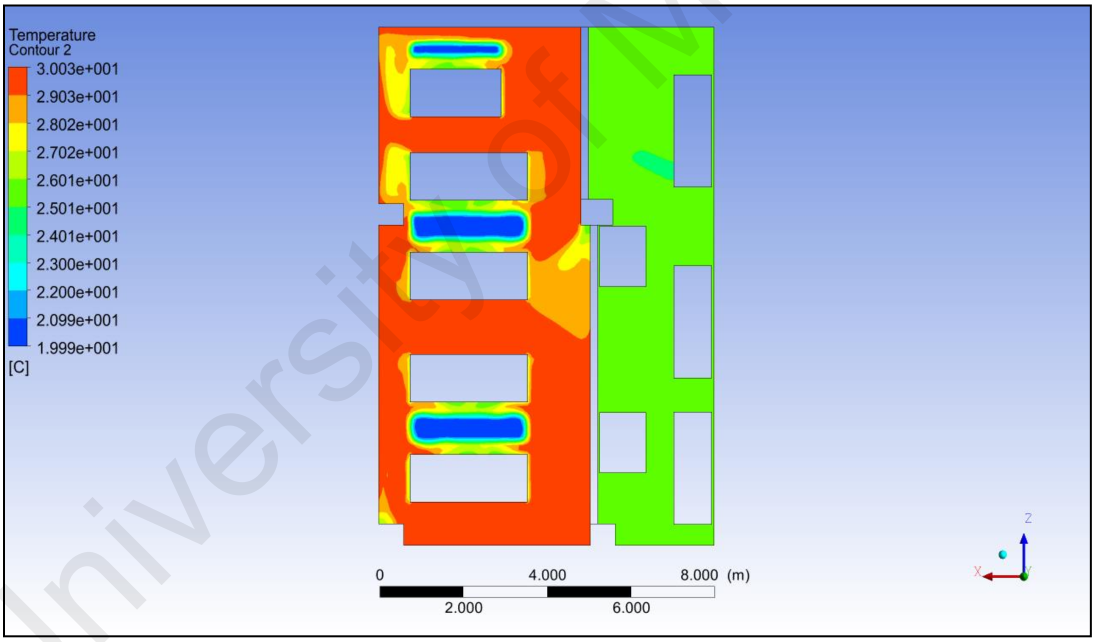

Figure 4.4: Heat distribution at floor level (0.1 m)

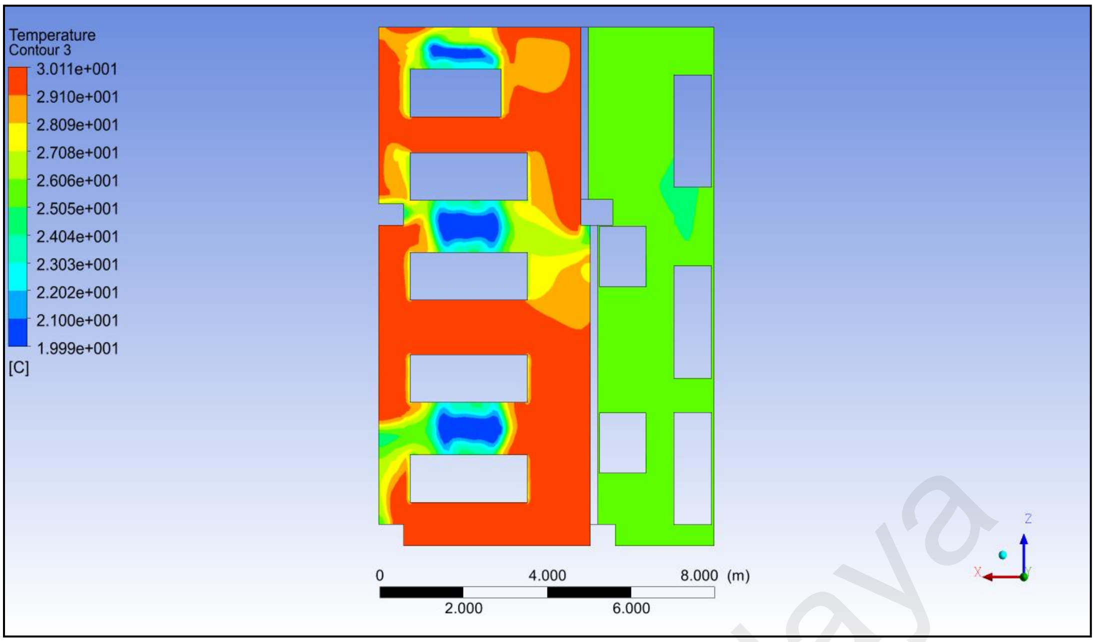

Figure 4.5: Heat distribution at mid-rack level (1.05 m)

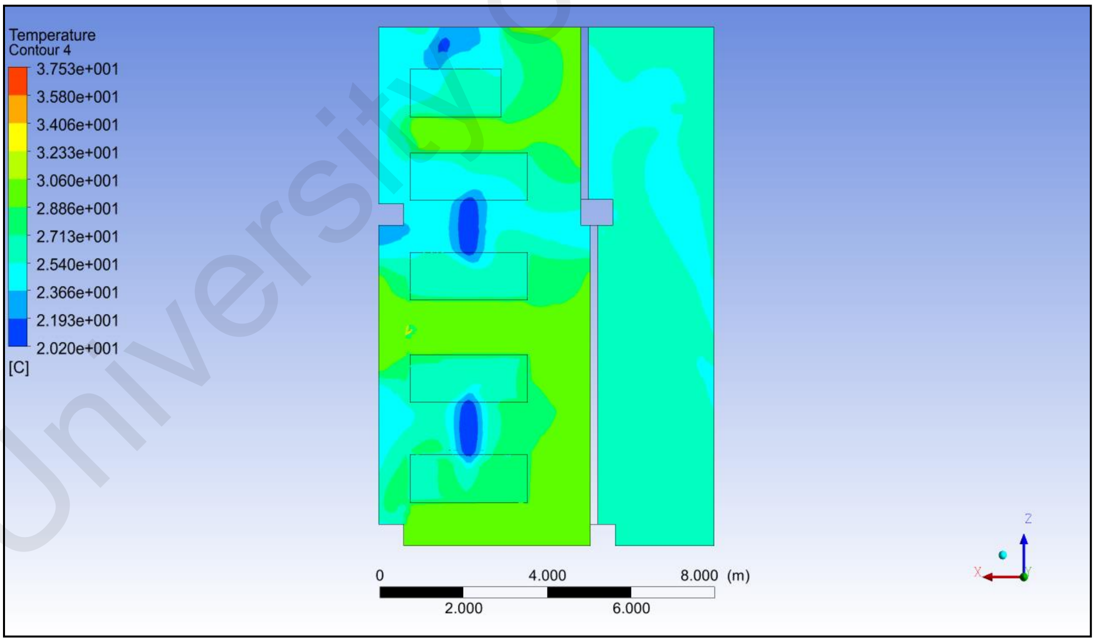

Figure 4.6: Heat distribution at top of rack level (2.09 m)

Apart from the heat distribution evaluation utilizing horizontal planes, vertical planes can also be used for assessment. Figure 4.7 shows the vertical planes location at 1.3 m, 4.75 m, and 6.8 m along the x-axis. These contours were anlyzed on various vertical planes to obtain a thorough insight into the airflow throughout the data centre

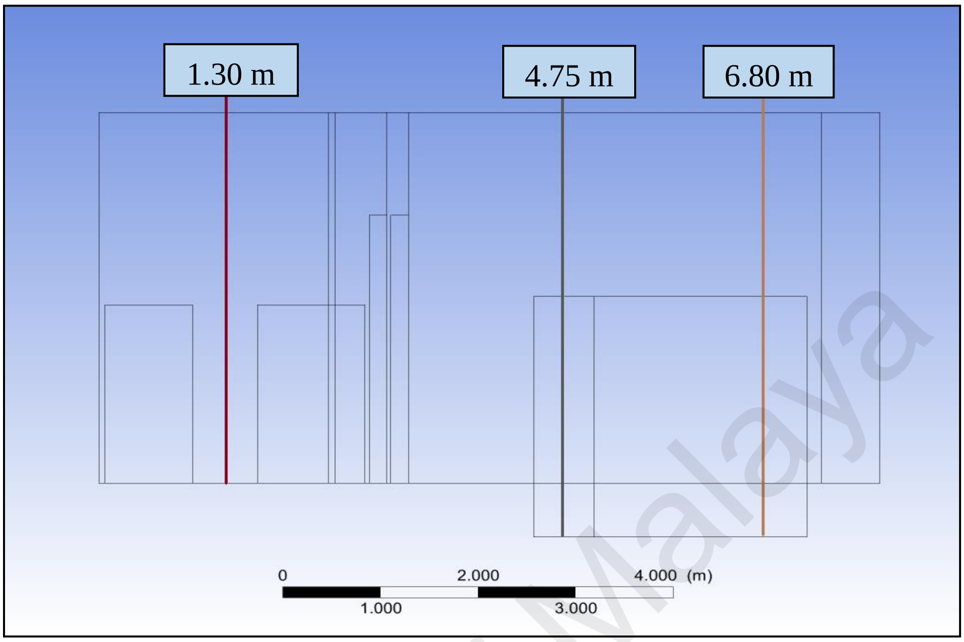

Figure 4.7: Vertical planes located at various locations across the data centre

The heat distribution along the vertical planes are exemplified in figures 4.8 – 4.10. The M&E room is averagely warm except for hotspots on top as shown in figure 4.8. This is due to the exhaust air flowing towards the inlet on top of the CRAC, which is in the room. On the planes located 4.75 m and 6.8 m along the x-axis as shown in figures 4.9 – 4.10, the server room is on the hotter side. Several hot air recirculation spots are observed at the upper portion of the server racks. The hot air recirculation will progressively increase the temperature of the cool air supplied. Consequently, this occurrence can be prevented by using the CACS method to isolate the hot and cold air effectively.

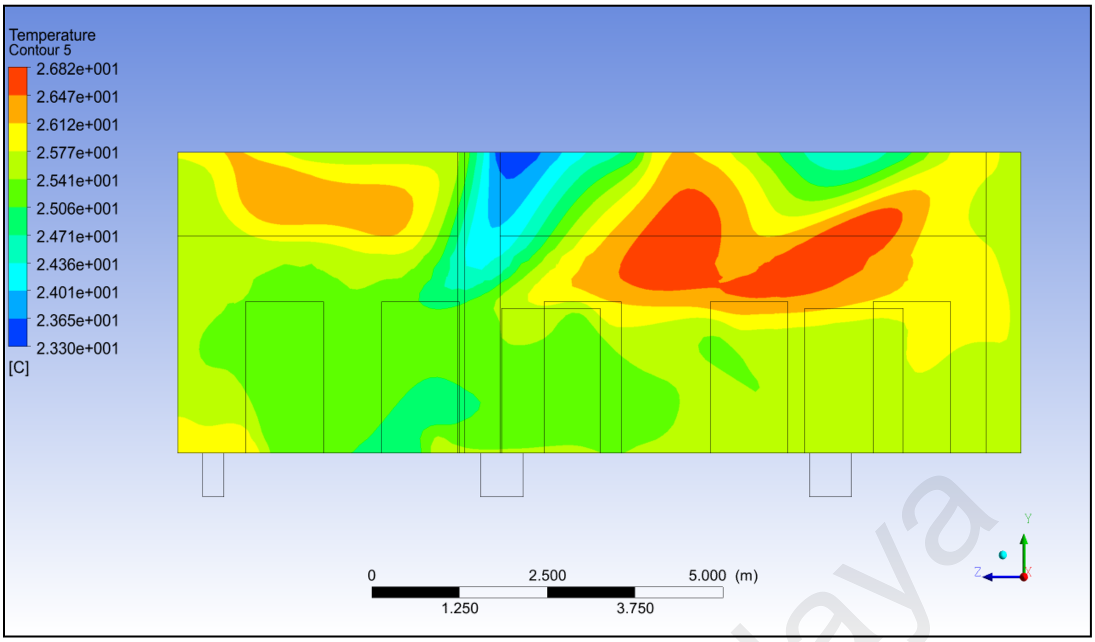

Figure 4.8: Vertical plane heat distribution (1.3 m along x-axis)

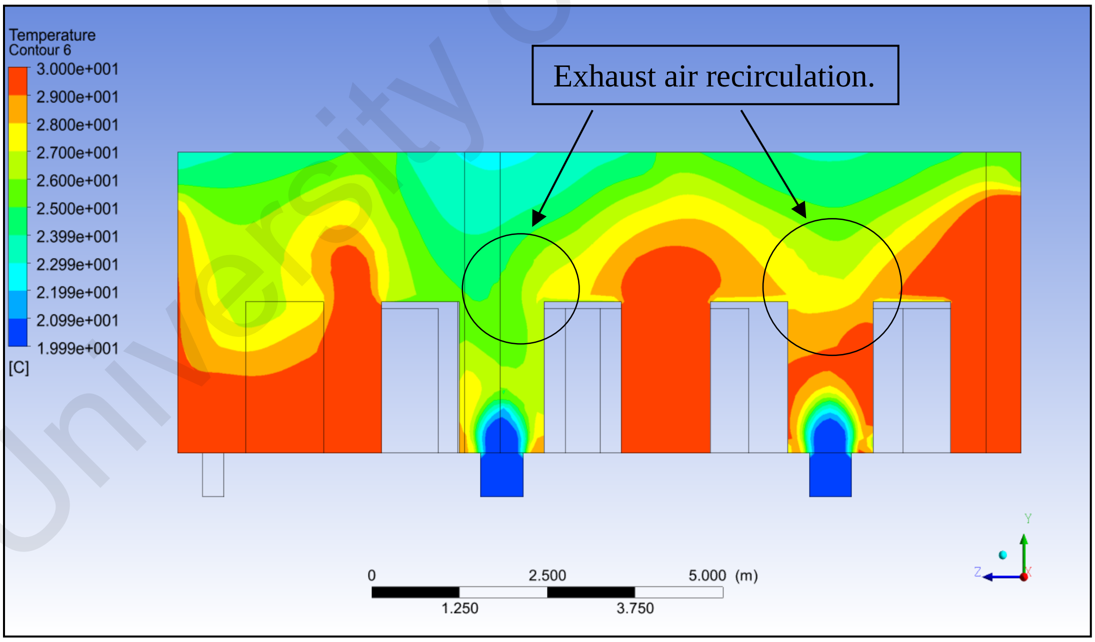

Figure 4.9: Vertical plane heat distribution (4.75 m along x-axis)

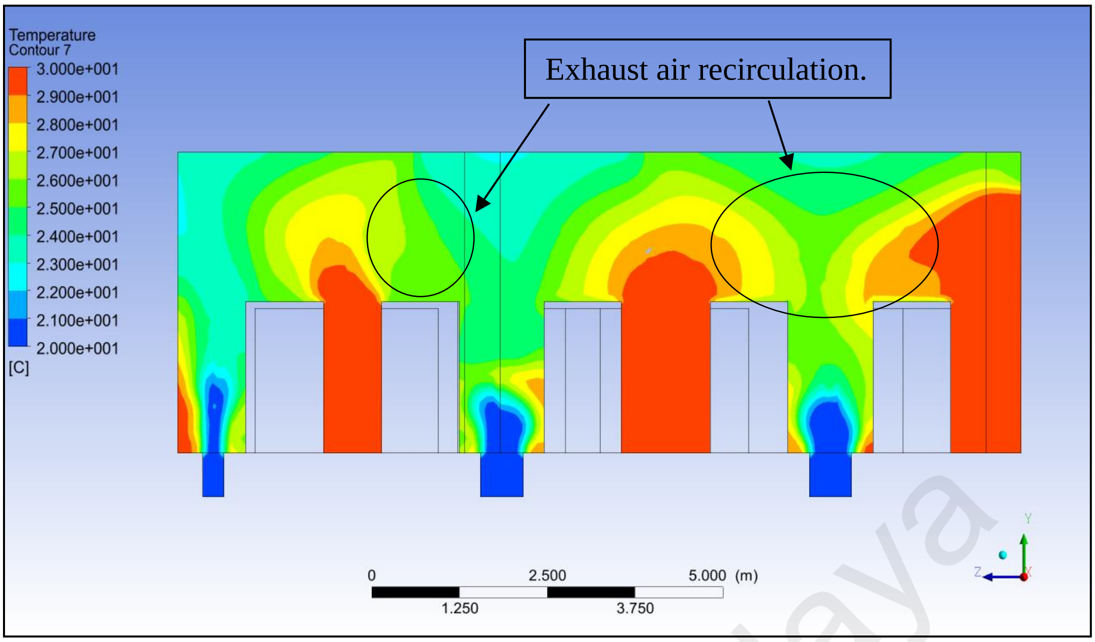

Figure 4.10: Vertical plane heat distribution (6.8 m along x-axis)

4.4 Simulation of Data Centre Equipped with CACS

The CACS method is employed to enhance the cooling efficiency by separating the hot and cold air streams. The panels installed will contain the cool air within the boundaries of the cold aisles. Figure 4.11 shows the temperature distribution at the server racks inlet complete with the CACS in place. Generally, the temperature ranges from 19.94 ^{o}C to 26.98 ^{o}C. The maximum temperature attained is just below ASHRAE's maximum suggested temperature of 27 ^{o}C. The temperature is lower overall and more uniformly disseminated with no visible hotspots unlike the initial setup. This is due to the exhaust air being unable to encroach into the cold aisles.

The cooling potential is increased without tweaking the CRAC infrastructure by reducing the amount of heat gained by the cool air. The cool air can be more efficiently distributed to the server rack inlets without being exposed to the hot air which increases its temperature gradually.

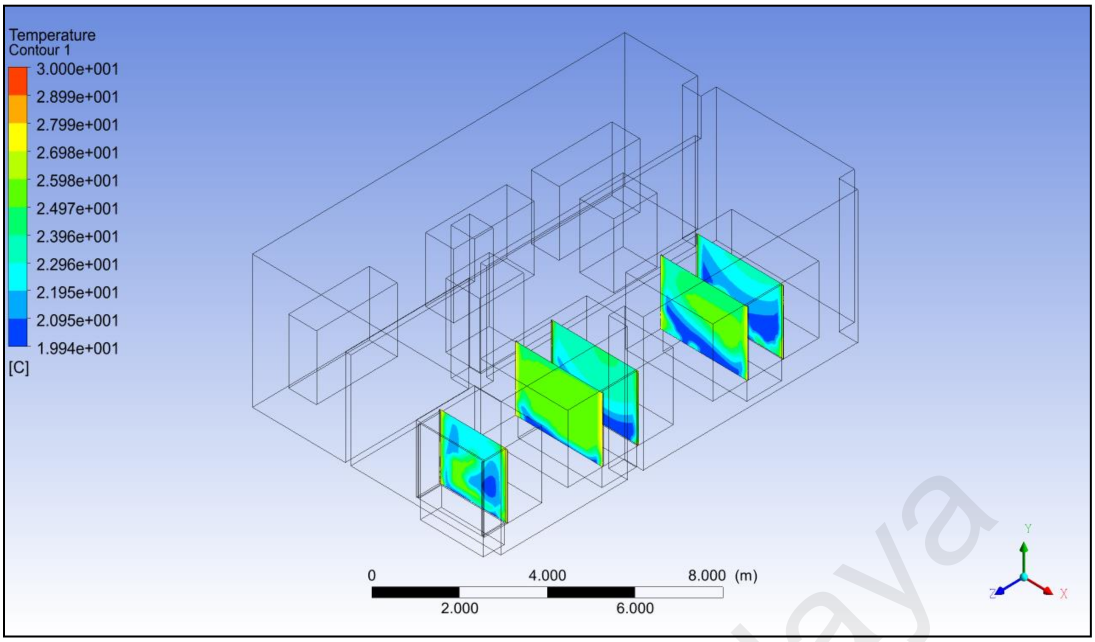

Figure 4.11: Temperature distribution at the CACS server racks' inlets

The temperature is better distributed using the CACS method as there is no exhaust air backflow from the rear to the front of these server racks. This is ascertained based on the exhaust air flow streamline in figure 4.12. The hot air swirls across the data centre, but only a small amount flows over the server racks with none entering the inlets. As a result, the occurrence of exhaust air recirculation is eradicated by the CACS. Hence, the data centre cooling efficiency is enhanced, and the temperature distribution is more consistent in the cold aisles.

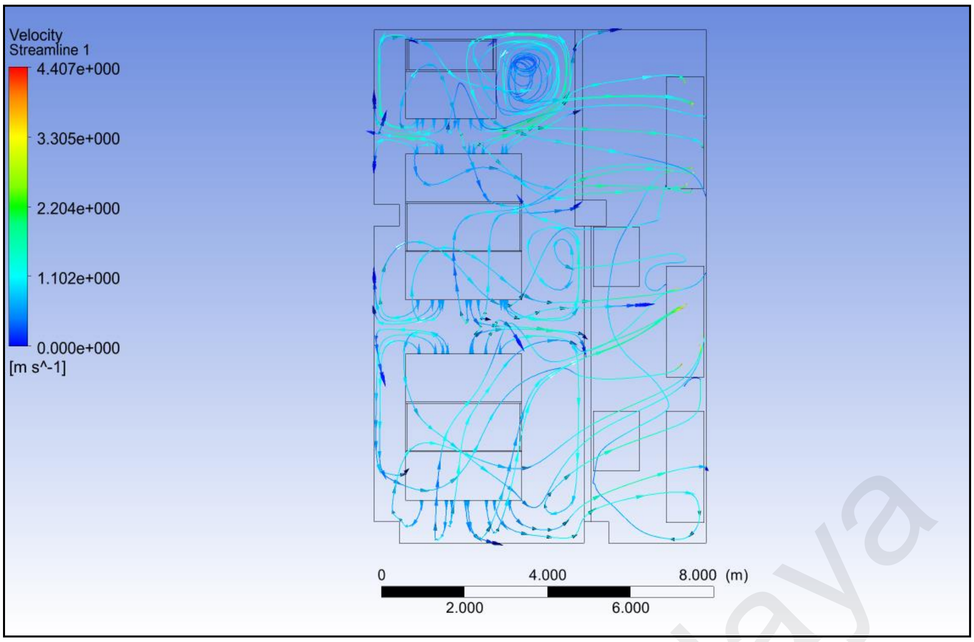

Figure 4.12: Exhaust air flow streamlines in the CACS equipped data centre

Figures 4.13 to 4.15 illustrate the heat distribution on horizontal planes at different server rack levels. It is observed that the temperature across the data centre is much higher compared to the initial setup without the CACS. This is due to the cool air being contained within its boundary by the CACS, which makes the entire data centre an exhaust air return plenum. The temperature across the data centre has a minimum of 28.35 ^{o}C and a maximum of 30 ^{o}C. This shows that without the mixture of hot and cold air, the temperature across the data centre spiked up due to the entirety of air being hot.

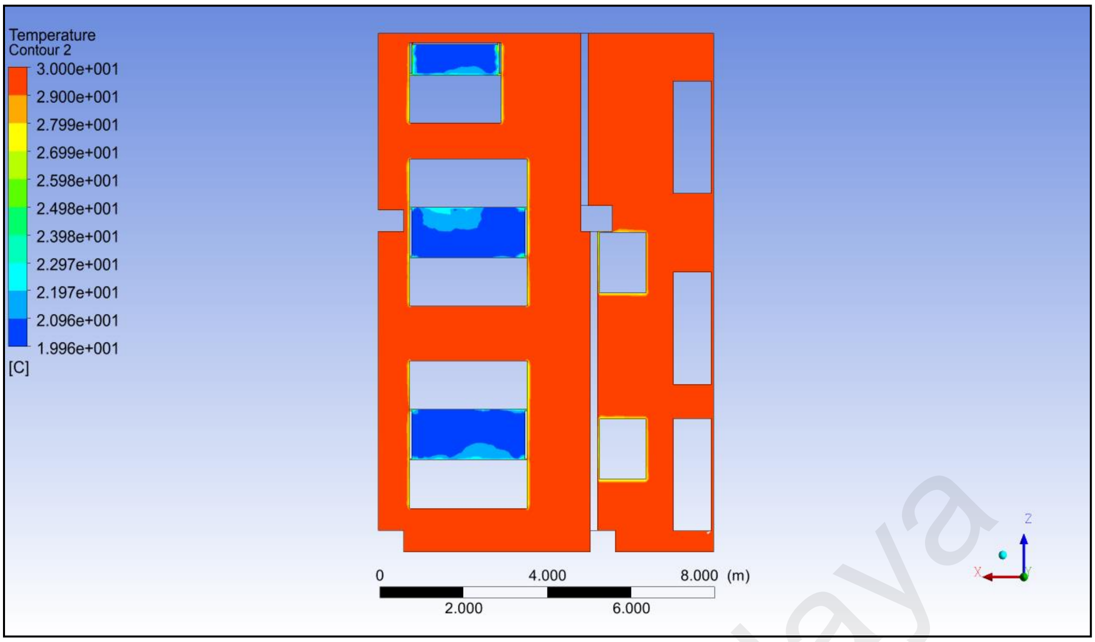

Figure 4.13: CACS heat distribution at floor level (0.1 m)

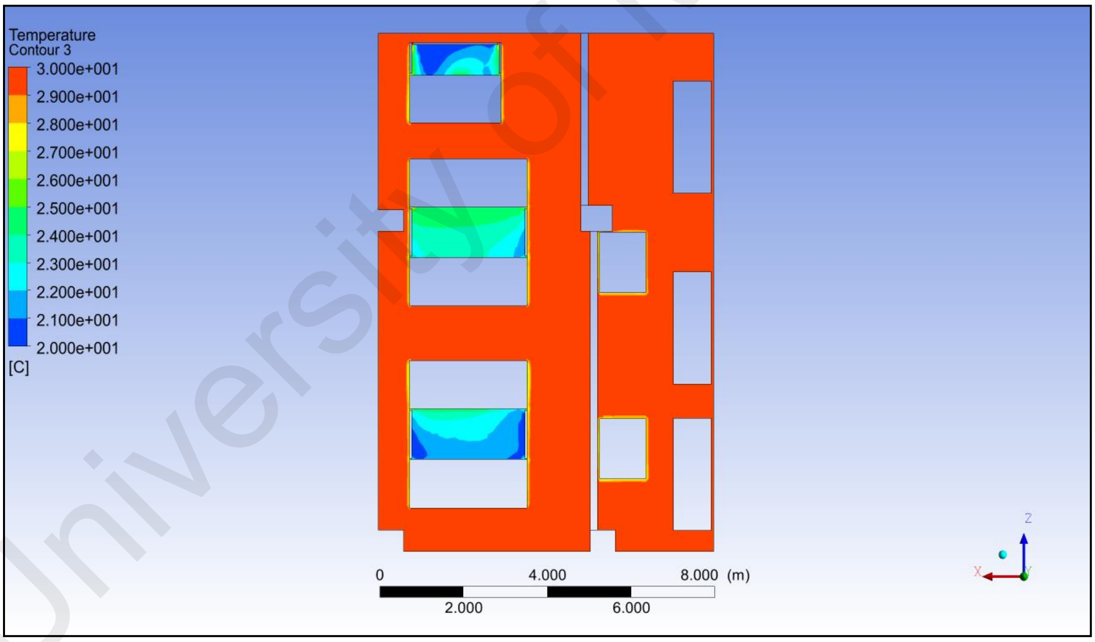

Figure 4.14: CACS heat distribution at mid-rack level (1.05 m)

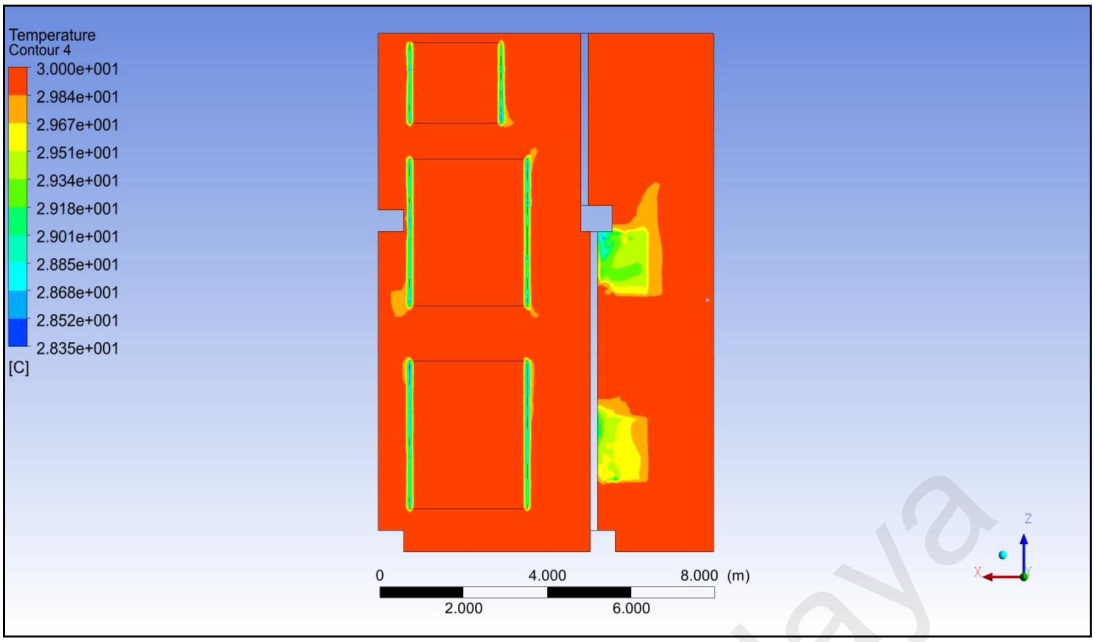

Figure 4.15: CACS heat distribution at top of rack level (2.09 m)

The heat distribution is inconsistent in the M&E room as shown in figure 4.16. The temperature is close to the maximum of 30 °C and the variation in the temperature contour identifies the locales of the heat concentration. In the server room, the maximum temperature is reached throughout the entire area as illustrated in figures 4.17 - 4.18. The cold air enclosure effectively contains the cool air without leakage to the surroundings of the server room. Consequently, the hot air recirculation incidence is resolved, and the temperature at the inlet of the server racks is lowered and distributed uniformly.

It was also observed that the temperature of the CACS server room has risen considerably compared to the initial setup. This is because the cool air is being hindered from mixing with the hot air to absorb its heat and lower the temperature. The temperature increase can be detrimental to other components in the data centre if the temperature is above its optimal operating temperature limits. Hence, proper design considerations need to be made to ensure that the CACS does not interfere with the components and lower the efficacy of the data centre.

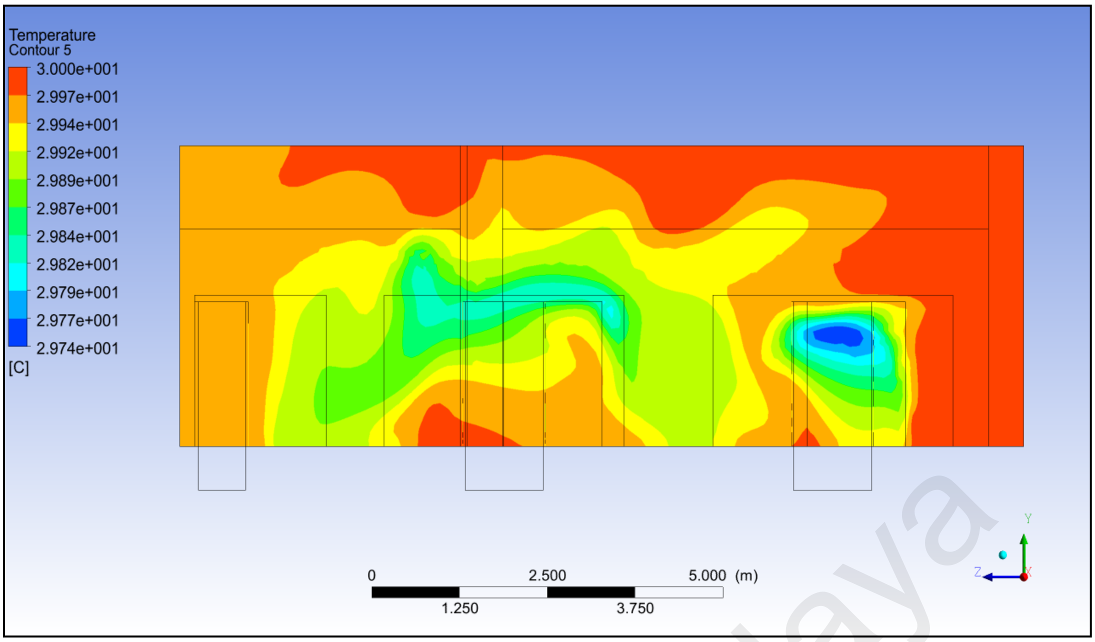

Figure 4.16: CACS vertical plane heat distribution (1.3 m along x-axis)

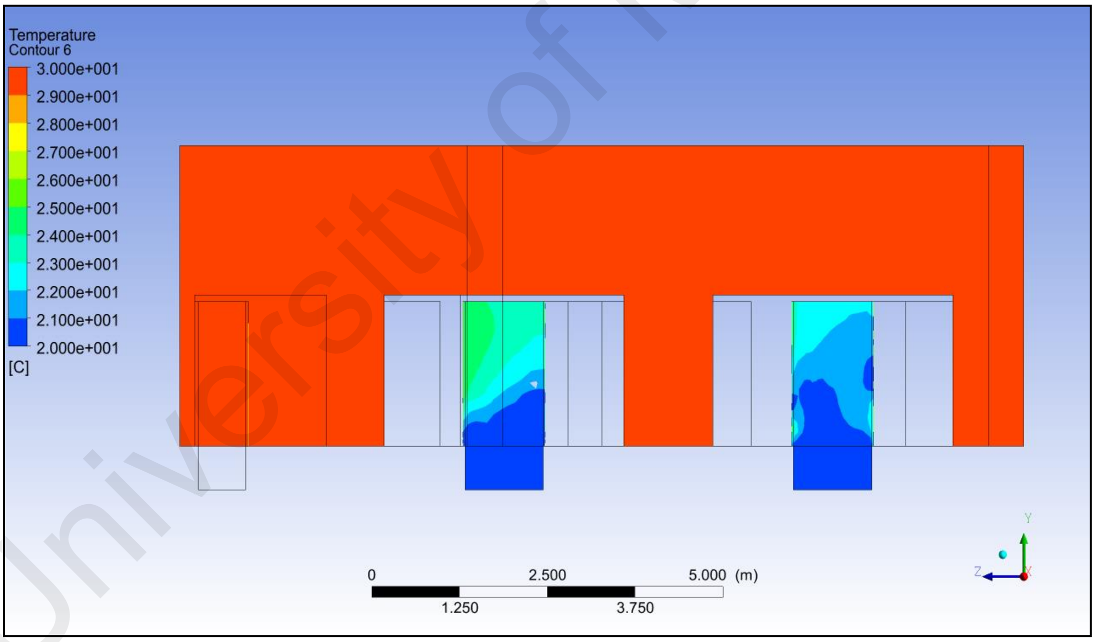

Figure 4.17: CACS vertical plane heat distribution (4.75 m along x-axis)

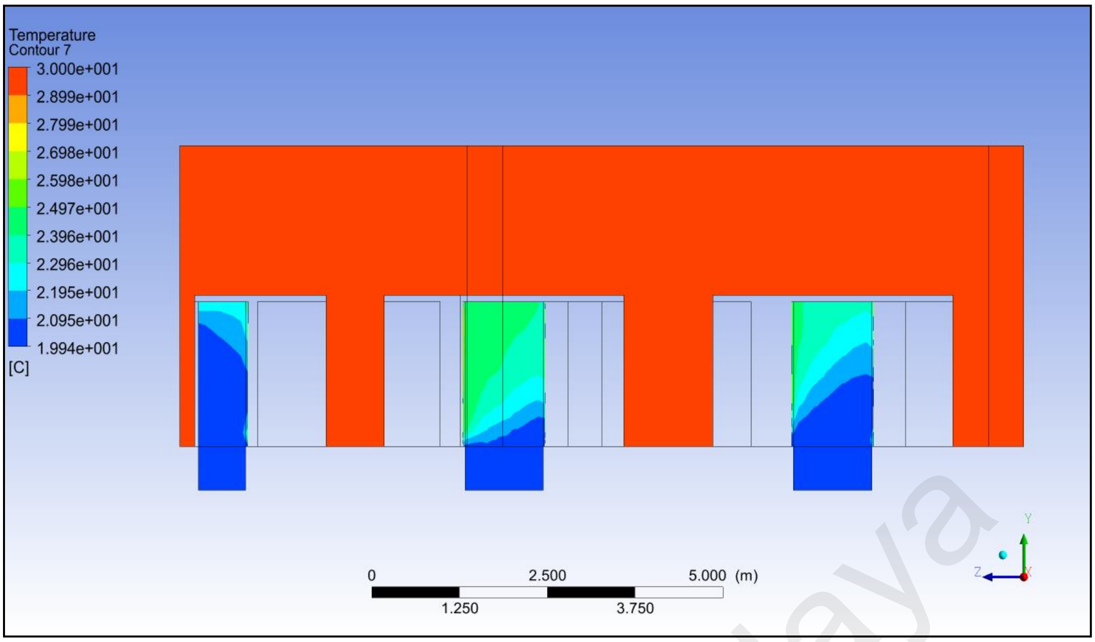

Figure 4.18: CACS vertical plane heat distribution (6.8 m along x-axis)

4.5 Results Comparison

The simulation results will differ compared to the results obtained at TM City's data centre 3. Based on the actual results from the data centre, the server racks' inlet temperature reached a maximum of 28.06 ^{o}C. In contrast, the simulation of the initial setup yielded a value of 29.79 ^{o}C. This shows that the simulation results have a deviation percentage of 6.17 % in comparison to the actual results. The deviation percentage signifies the proximity of both the results that were obtained through diverse methods. Nonetheless, it must be noted that external fittings such as lighting and cabling were omitted from the simulation design.

CHAPTER 5: CONCLUSION & RECOMMENDATIONS

5.1 Conclusion

TM City's data centre 3 was designed and simulated in a three-dimension environment based on the two-dimensional schematic. An assessment into the cooling was done based on results yielded from the CFD simulations. The temperature contours showed that hotspots were concentrated at the upper region and sides of the server racks albeit lower temperatures were recorded at the lower region of these racks. The hotspots indicated high temperatures that were due to the exhaust air recirculation from the hot aisles into the cold aisles which was justified by the velocity streamline of the airflow within the data centre. The server rack inlets had an average temperature of 25.18 ^{o}C.

As a technique to improve cooling effectiveness, the initial data centre setup was recommended to be fitted with a CACS to eliminate the occurrence of exhaust air recirculation. The CFD simulation results for the CACS equipped data centre showed that the CACS prevents the exhaust air from recirculating. Also, the temperature is lowered and distributed evenly at the server racks' inlets, where its average temperature was 23.46 ^{o}C. This shows that the CACS setup made a cooling improvement of 6.83% compared to the initial setup. The CACS approach managed to improve the cooling efficiency at without needing to upgrade the CRAC system.

As the research has demonstrated, TM City data centre 3 performs averagely, but with the addition of the CACS, the cooling was improved remarkably. A containment system can boost the effectiveness of a data centre, except that factors such as its high cost, and space requirement can be a hindrance. Feasibility studies should be done in depth to ascertain the need for these enclosure systems.

5.2 Recommendations

In this research, the geometry was simplified by assuming all the components are rectangular boxes and modelled as black boxes. This was done to minimise the time consumed and computing power needed to run the CFD simulations. Though, the drawback of this approach is that the results yielded can be less accurate. It is recommended to simulate the data centre based on its actual build and include external fittings such as lighting and cabling.

The simulation section is vital to the research. The settings chosen in this segment will either make the results more or less accurate. Among the options that will have a significant impact on the output results are turbulent models, type of pressure velocity coupling and mesh refinement. It is suggested to tweak the settings accordingly to achieve results that are closer to a physical data centre.

The cooling medium is an important aspect of data centre cooling. Air is widely used as it is a safe option that does not degrade components. The other alternative is liquid based cooling. Although it is not widely used like air, it has potential to be a critical medium of cooling. A good recommendation would be to comprehensively evaluate both, liquid and air, using numerical simulations. Based on the results, the medium that is cheaper overall and more efficient can be identified.

REFERENCES

ANSYS. (2010). Lecture 6: Turbulence Modeling. In *Introduction to ANSYS FLUENT*.

ANSYS. (2013). ANSYS Fluent Theory Guide. Retrieved from http://www.pmt.usp.br/academic/martoran/notasmodelosgrad/ANSYS%20Fluent%20Theory%20Guide%2015.pdf

ANSYS. (2014). Meshing Solutions. Retrieved from https://www.ansys.com/-/media/ansys/corporate/resourcelibrary/brochure/ansys-meshing-brochure.pdf

ASHRAE. (2011). Thermal Guidelines for Data Processing Environments – Expanded Data Center Classes and Usage Guidance.

Athavale, J., Yoda, M., & Joshi, Y. (2018). Chapter Three - Thermal Modeling of Data Centers for Control and Energy Usage Optimization. In E. M. Sparrow, J. P. Abraham, & J. M. Gorman (Eds.), *Advances in Heat Transfer* (Vol. 50, pp. 123-186): Elsevier.

Chu, W.-X., & Wang, C.-C. (2019). A review on airflow management in data centers. *Applied Energy, 240*, 84-119. doi:https://doi.org/10.1016/j.apenergy.2019.02.041

Godderidge, B., Tan, M., Turnock, S., & Earl, C. (2006). A verification and validation study of the application of computational fluid dynamics to the modelling of lateral sloshing.

Henessy, D. (2016). Virtual Notions - DC & Cloud Musings Retrieved from https://www.vnotions.com/tag/data-centre-user-group-melbourne/

Jr., J. D. A., Degroote, J., Degrez, G., Dick, E., Grundmann, R., & Vierendeels, J. (2009). *Computational Fluid Dynamics: An Introduction* (J. F. Wendt Ed. Third ed.): Springer - Verlag Berlin Heidelberg.

Lin, J., Richards, D., Talbot, C., Yeh, G.-T., Cheng, R., Cheng, H.-P., & Jones, N. (1997). FEMWATER : A Three-Dimensional Finite Element Computer Model for Simulating Density-Dependent Flow and Transport in Variably Saturated Media.

Nada, S. A., & Said, M. A. (2017). Effect of CRAC units layout on thermal management of data center. *Applied Thermal Engineering, 118*, 339-344. doi:https://doi.org/10.1016/j.applthermaleng.2017.03.003

Nada, S. A., Said, M. A., & Rady, M. A. (2016). CFD investigations of data centers' thermal performance for different configurations of CRACs units and aisles separation. *Alexandria Engineering Journal, 55*(2), 959-971. doi:https://doi.org/10.1016/j.aej.2016.02.025

Niemann, J., Brown, K., & Avelar, V. (2011). *Impact of Hot and Cold Aisle Containment on Data Center Temperature and Efficiency: Revision 2 [White Paper 135]*. Retrieved from http://www.facilitiesnet.com/whitepapers/pdfs/APC_011112.pdf

Ozen, M. (2014). Meshing Workshop. In: Ozen Engineering Inc.

Primefloor. (2018). Raised Floors. Retrieved from https://www.primefloorksa.com/dt_gallery/raised-floors/

Rasmussen, N. (2014). *Raised Floors vs Hard Floors for Data Center Applications: Revision 3 [White Paper 19]*. Retrieved from https://download.schneider-electric.com/files?p_Doc_Ref=SPD_SADE-5TNQYN_EN

Rehm, B., Schubert, J., Haghshenas, A., Paknejad, A. S., & Hughes, J. (2009). *Managed Pressure Drilling*. Houston, Texas: Gulf Publishing Company.

Sadrehaghighi, I. (2020). *Assessment of Meshing Types & Mesh Quality*.

Sharma, R., Bash, C., & Patel, C. (2002). Dimensionless Parameters for Evaluation of Thermal Design and Performance of Large-scale Data Centers. *Proceedings of The IEEE - PIEEE*. doi:10.2514/6.2002-3091

Technologies, B. N. (n.d.). Retrieved from http://www.bluewavenetwork.net/data-centers.html

Thompson, J. F., Soni, B. K., & Weatherill, N. P. (1999). *Handbook of Grid Generation*. USA: CRC Press LLC.

Wibron, E., Ljung, A.-L., & Lundström, S. (2016). *CFD Simulations Comparing Hard Floor and Raised Floor Configurations in an Air Cooled Data Center.* Paper presented at the 12th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics.

Wilcox, D. C. (2006). *Turbulence Modeling for CFD* (3rd ed.). California, USA: DCW Industries, Inc.